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Advances in the integration of solar thermal energy with conventional and non-conventional power plants

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ABSTRACT

Pollution and increasing fuel prices are the main focus for governments today. The main cause of pollution is existing electricity power plants that use huge quantities of fossil fuel. A new strategy should be applied in the coming decades based on the integration of existing power plants with renewable energy sources, such as solar and wind energy. Hybridization of existing power plants with solar energy is one proven option to overcome the problems of pollution and increasing fuel prices. In this paper, a review of the previous studies and papers for integrating solar thermal energy with conventional and non-conventional power plants was carried out. The focus on hybrid solar conventional power plants includes: the review of studies of hybrid solar–steam cycle power plants, integrated solar combined-cycle systems (ISCCS) and hybrid solar–gas turbine power plants, while for hybrid solar non-conventional power plants the focus of study is hybrid solar–geothermal power plants. The most successful option is ISCCS due to their advantages and the plans for implementation at various power plants in the world like in Tunisia, Egypt, Spain, and Iran.

Contents

1. Introduction

With rapid depletion of fossil fuel reserves and their marked effects on the environment, the use of renewable energy sources needs to be accelerated. Therefore it is necessary to find adequate substitutes and plan a transition to other energy sources that provide minimum environmental impact and are available in sufficient quantities in order to satisfy demand and ensure the security of energy supplies. Solar energy is gaining more and more attention as a clean, free, and non-depleting source. However, the application of solar energy for power generation purposes is costly compared to conventional electricity generation systems, thus a new approach is needed to overcome this challenge.

Abbreviations: PTC, Parabolic trough collector; SH, Superheater; CLFR, Compact linear fresnel reflector; EC, Economizer; FPC, Flat Plate Collector; RH, Reheater; SCR, Solar central receiver; AH, Air Heater; ETC, Evacuated tubular collector; TSS, Thermal storage system; DSG, Direct steam generation; RC, Rankine cycle; HTF, Heat transfer fluid; CC, Combined cycle; FWH, Feed-water heater; GT, Gas turbine; EV, Evaporator; HP, High pressure; ISCCS, Integrated solar combined cycle system; IP, Intermediate pressure; SEGS, Solar electric generating system; LP, Low pressure; SD, Solar dishes; SAPG, Solar aided power generation; STS, Solar thermal system; ST, Steam turbine; STGHS, Solar thermal geothermal hybrid system; HRSG, Heat recovery steam generator

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Approximately 66% of world electricity production comes from fossil fuel power plants, such as steam-cycle power plants, combined-cycle (CC) power plants, and gas-turbine (GT) power plants that are also main sources of pollution [1]. Hybridization is an attractive option, using both solar energy and fossil fuels concurrently. In this paper, a review of studies and papers carried out since the 1970s until recently, on the integration of solar thermal energy with conventional and non-conventional power plants, is presented. Issues and advantages of the hybridization of solar thermal power in electricity generation was reviewed, described, and analysed by Williams et al. [2]. Four options for hybridization were compared, namely, redundant system hybridization, parallel fossil heater hybridization, solar augmented hybridization, and solar preheat hybridization. It was reported that well-designed hybrid plants can have significant advantages over solar only plants, particularly for near term markets. These advantages include the opportunity for higher energy conversion efficiency, lower capital investment in new technology, higher valued energy due to dispatchability, and lower energy costs.

2. Integration of solar thermal with conventional power plants

A methodology for structuring solar thermal power plants into sub-systems towards a standardized modelling approach was presented by Hirsch et al. [3]. The purpose of this study was to define guidelines for modelling, simulation and assessment of such systems focused on the following types: solar central receiver (SCR), parabolic trough collector (PTC), compact linear Fresnel collectors (CLFC) and solar dishes (SD). These terms are used here to make comparisons between the different types of hybrid systems. Three types of conventional power plants were selected as power blocks for integration with different types of solar thermal systems as described in the following sections.

2.1. Hybrid solar–steam power plants

In this section, a review of previous studies on the hybridization of Rankine cycle (RC) with solar thermal energy is presented. In general, the early work started in 1975 with Zoschak and Wu [4] studying seven methods of absorbing solar energy as the direct thermal input to an 800 MW fossil-fuelled central station steam power plant. SCR was chosen by the authors as the solar collecting field. The heat absorbing methods studied were feed-water heating, evaporation of water, superheating of steam, combined evaporation and superheating, reheating of steam, air preheating, and combined air preheating and feed-water heating. The heat balance for new hybrid cycles was carried out by General Electric Company. Their results showed the combined evaporation and superheating to be the preferred method for hybridization. Griffith and Brandt [5] developed a computer model to account for the energy flows and economics within a solar–fossil fuel hybrid power plant using a thermal storage system (TSS). The model calculated the power from an SCR on an hourly or quarter-hourly basis and determined the quantity of solar power directed to the TSS, the quantity of solar power directed to a specified load, the amount of power retrieved from the TSS, and the mass of fuel used by the fossil portion of the hybrid power plant. They showed the capital investment for a solar–fossil fuel hybrid system should not exceed 2.5 times the present value of the capital investment for a comparable fossil fuel power system if the hybridization is to be economically competitive.

Pai [6] proposed integration of a solar concentrator field to a 210 MWe coal-fired power plant by adding heat exchangers before each feed-water heater, as shown in Fig. 1. His results showed a 24.5% saving in fuel during the period of insolation through the heating of the feed water heater (FWH) by solar energy. Odeh et al. [7] modelled an alternative arrangement of the solar collector field and the power house back-up boiler. The model was linked with the direct steam generation (DSG) trough collector model to evaluate the best collector-back-up boiler arrangement. Their analysis showed that the solar energy contribution will be at the maximum if the collector is operated as a boiler.

Ying and Hu [8] modified a regenerative-reheat Rankine power cycle to use low temperature solar energy and other low temperature heat sources as the main heat source. Morrison et al. [9] studied the integration of CLFR into a Stanwell coal-fired power plant in Australia, they observed that the new CLFR has the potential to deliver the lowest cost solar thermal electric power compared to all solar thermal power systems. Ying and Hu [10] reported the thermodynamic advantages of using solar energy as an auxiliary heat source in a regenerative RC power plant. It was proved that the exergy merit index of the energy hit extremely high values that are far superior to the corresponding exergy efficiencies in other power systems with the same waste heat as the heat source alone. Hence, the solar aided system can run more efficiently than a conventional regenerative RC plant. It was also shown that making heat carriers in different temperatures with different types of collectors is relatively easy. In another paper, Ying and Hu [11] analysed the reheat–regenerative RC, investigating the optimal thermal and exergetic efficiencies for the combined system of the power cycle and collector, the optimum saturation temperature in the boiler and the optimum temperature of the fluid entering the solar field. It was found that a reheat–

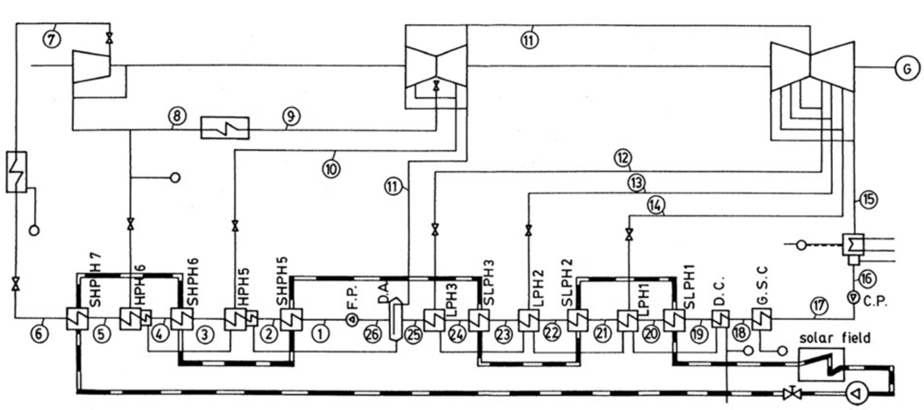


Fig. 1. Integration of solar concentrator field to conventional steam power plant by adding shell and tube heat exchangers before feed-water heaters [6].

regenerative arrangement is suitable for medium-temperature solar hybrid power generation.

Hu et al. [12] developed software named THERMOSOLV, capable of reporting the technical and economic feasibility of solar aided concepts for various steam power plant configurations, for various locations, and various collector types. Hu et al. [13] proved that solar aided power generation is an effective method of utilizing low-grade solar thermal energy, both technically and economically as the existing infrastructure of a conventional power station would be utilized. Savings in fuel were also observed to be directly proportional to CO_2 reductions. Odeh et al. [14] developed a model of a solar electric generating system (SEGS) in order to study different arrangements of a DSG collector field power house under Australian conditions. Fig. 2 shows one of the proposed integration schemes. Bockamp et al. [15] studied the integration of CLFC for different types of power plant including steam and CC power plant using TRANSYS software, finding that the benefit of such hybridization was a reduction of cost of electricity and reduction in fuel consumption. Yinghong et al. [16] studied hybridization of the RC with PTCs, their results showed that feed water preheating is more economical in large units than in others as well as improving the cycle efficiency. They also studied chosen designed solar radiation for different locations. Yang et al. [17] studied the methods and mechanism of the integration of PTCs with coal-fired power plants using a built up integration and optimization model. An economic evaluation was also carried out and showed that the new integrated system has lower generation costs compared to conventional coal-fired power plants. Tora et al. [18] developed a systematic design procedure to determine the optimal mix between fossil and solar energy in order to provide stable power output using integrated solar systems.

Gupta and Kaushik [19,20] analysed exergy characteristics for different components of a proposed conceptual solar thermal DSG power plant. Steam generated by a PTC was integrated with a thermal power plant to enter the steam turbine. They concluded that heating the feed-water of a thermal power plant using solar energy is more advantageous than using the same solar energy in stand-alone solar thermal power plants. Hu et al. [21] studied the advantages of the solar aided power generation (SAPG) concept in the aspects of its energy and exergy, using THERMOSOLV software, through hypothetical case studies. They proved that the energy and exergy efficiencies of the power station can be improved by using solar energy to replace the extracted steam in order to heat the feed-water in a regenerative RC. Qin Yan et al. [22] studied the overall efficiencies of the SAPG with different solar replacements of extraction steam at multi-points and multi-levels to replace parts of the steam extraction in the regenerative RC. It was found that solar integration assisted the power plant in reducing coal consumption and pollution emissions or in increasing the power output, also the solar thermal to electricity conversion efficiencies of the SAPG system are higher than those of solar only power plants with the same temperature level of solar input. Larrain et al. [23] developed a thermodynamic model to estimate the back-up fraction needed in a 100 MW hybrid solar–fossil PTC power plant. PTCs provided heated steam to the generator, and fossil fuel is the back-up energy resource. Monthly means of solar radiation were used by the authors to estimate the solar fraction and back-up requirement for four locations in Chile. They then recommended the best plant location based on the minimum fossil fuel fraction.

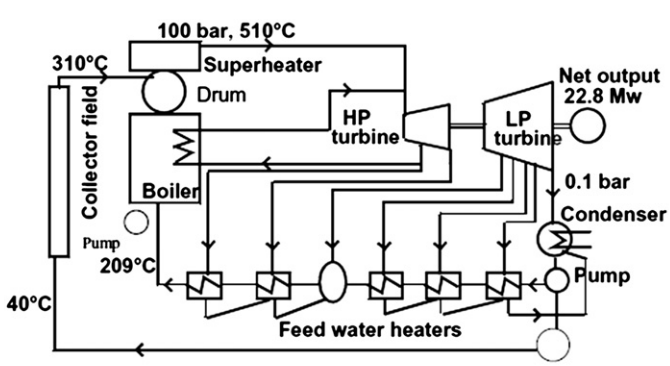


Fig. 2. Preheating-boiling integration scheme using direct steam generation technology [14].

Suresh et al. [24] analysed the energy, exergy, economic, and environmental impacts of hybrid solar–coal-fired subcritical and supercritical power plants in India using the Cycle Tempo software. The solar fields consisted of PTCs. It was shown that there is an instantaneous fuel conservation of about 5–6% with the substitution of turbine bleed streams to the feed-water heaters, with the best possible solar aided option being at the high pressure FWH. It was also observed that the utilization of solar energy for feed-water heating is more efficient based on exergy rather than energy analysis. Jun [25] analysed two types of integration arrangement for a 600 MW coal-fired power plant based on DSG technology; integration of PTCs with the boiler before and after the economizer. The results showed that the integration before the conomizer has more benefits compared to the later and is shown is Fig. 3. Popov [26] modelled three options to repower an existing 130 MW steam power plant with solar heat using THERMOFLEX software. His off-design calculations indicated that the most attractive option, especially for the existing power plant solar repowering, is a plant with high pressure (HP) heaters replaced by a solar field, this case assumed feed-water preheating from about 168 °C up to 249 °C, this option needs almost 'zero' power plant modification and proposed large solar power generation share, large fossil fuel savings and high power plant efficiency.

Xiuyan et al. [27] proposed using solar steam to be the auxiliary thermal source of a 600 MW coal-fired supercritical unit by integration to the de-aerator, and showed an increase in thermal efficiency with a reduction in fuel consumption. Yang et al. [28] demonstrated SAPG through a case study of a 200 MW coal-fired power plant. Four replacement schemes were studied, and the most efficient way to make use of solar heat in the medium and low temperature range for power generation was by replacing the bled-off steam in the regenerative RC. It was also shown that the benefits of SAPG can be realized in two ways; when the solar integrated coal-fired power station is operated at power boosting mode or fuel saving mode. Reddy et al. [29] carried out a comparative energetic and exergetic analysis of a solar aided coal-fired supercritical thermal power plant using CLFR. It was observed that there was an instantaneous increase in power generation capacity of about 20% when substituting turbine bleed streams for all the low pressure and HP FWHs.

Yan et al. [30] developed a model to evaluate SAPG, studying the energy and economic benefits for integration of solar heat to preheating feed-water in the range from 90 °C to 260 °C with 200 MW and 300 MW as typical, 600 MW as subcritical, 600 MW as supercritical, and 600 MW and 1000 MW as ultra-supercritical fuel power units separately. The results indicated that the benefits of SAPG vary for different steam extracted positions and different power plants. Generally, the larger the power plant, the higher the benefit for the same level of integrated solar power. Camporeale et al. [31] examined the repowering of an existing steam power plant using solar concentrating collectors, and showed the benefit of this integration from a thermodynamic viewpoint.

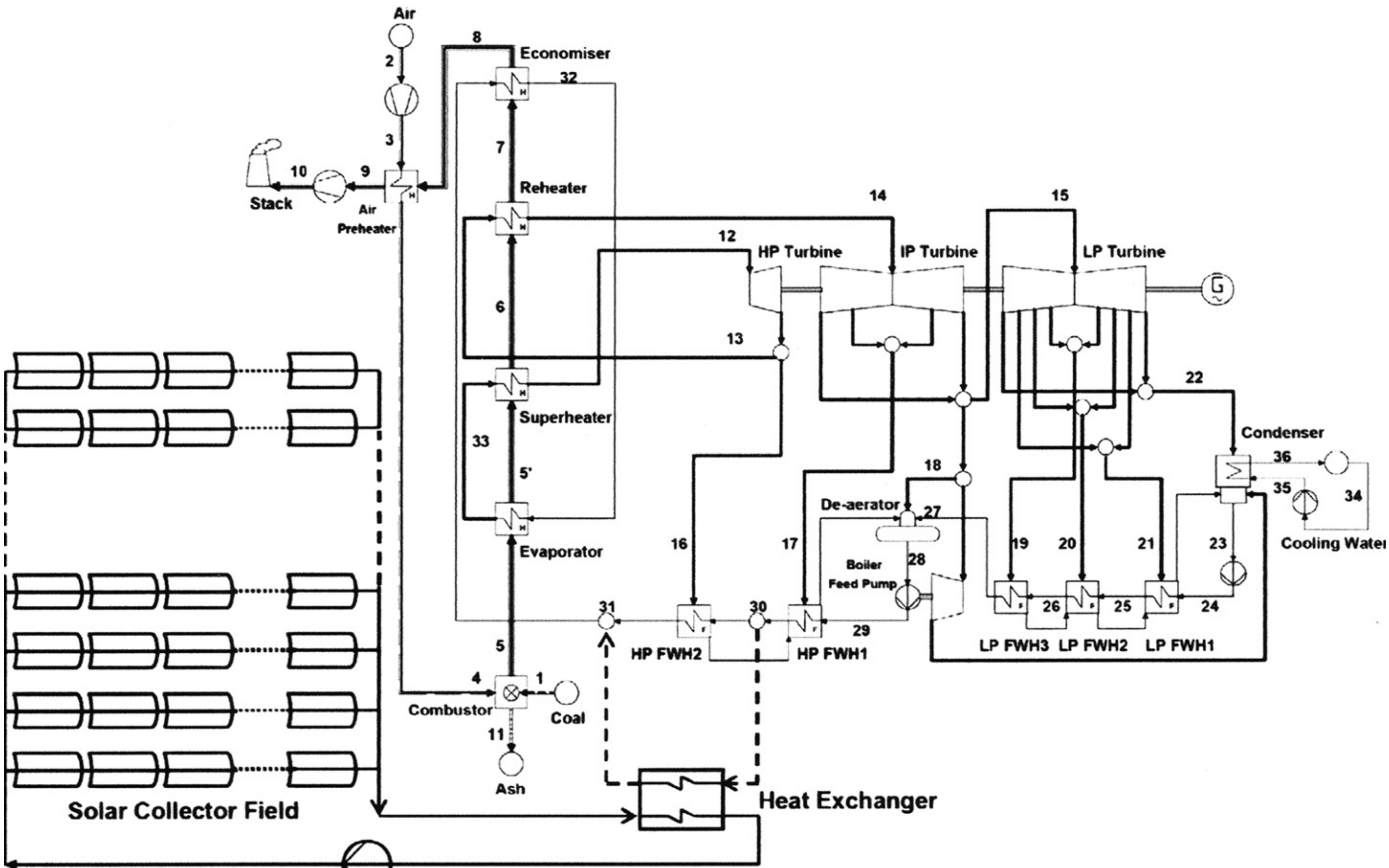


Fig. 3. Feed-water preheating for conventional coal-fired power plant using heat transfer fluid (HTF) technology.

2.2. Hybrid solar–CC power plants

The concept of the integrated hybrid solar–CC power plants started in the early 1990s, initially proposed by Luz Solar International as a means of integrating PTCs with modern CC power plants [32].

Many authors have carried out studies and published many papers in this field. This new concept of the integrated hybrid solar–natural gas CC was first studied by Allani [33]. Rheinlander et al. [34] suggested several schemes for integration of solar technologies that supply low temperature energy into CC supplemental solar heat to the bottoming RC. Bhon et al. [35] proposed solar preheating at the topping Brayton cycle. They showed that this scheme offers high conversion efficiency but limited solar contribution to the plant's overall electricity production. Price et al. [36] proposed a hybrid solar tower system using high concentration optics and high temperature air receivers to drive the CC power plant. They showed that the solar energy is used at a high exergy level as a heating source for the topping GT cycle. Allani et al. [37] evaluated an integrated hybrid solar–fossil CC from a technical and economic risk feasibility standpoint for possible implementation as a pilot plant in Tunisia, using the thermo-economic optimization approach. They found that this approach shows several advantages for this type of design when compared with a purely solar steam cycle or any of the various other hybrid solar concepts existing at that time.

Kolb [38] examined the economic potential of using different configurations of hybrid and solar only power plants. SCR integrated to CC and coal-fired power plants, their results showed the hybrid plants are more economical compared with solar only power plants. Kribus et al. [39] presented a CC electricity generation plant driven by highly concentrated solar energy and high temperature SCR technology. They showed that the new system design has cost and performance advantages over other solar thermal concepts, and can be competitive against conventional fuel power plants. Kane et al. [40] developed a thermodynamic optimization model based on a pinch technology approach for the synthesis, design and operation of advanced solar–fossil CC power plants. The developed model includes a steam cycle with single or multiple steam evaporation pressure levels. Their calculations were carried out for different configurations of steam turbines and for different operation modes of an 80 MWe to 125 MWe ISCCS taking into account annual plant performance and the simplicity of the operations, with an economic costing and sensibility analysis. Their results showed that the solar electricity costs are higher than those of a similar sized CC, and the hybrid solar thermal power plants may already be competitive against conventional fuel fired power plants. Kelly et al. [41] studied integrated CC–solar plant designs using the Gate Cycle software. Their results showed that the most efficient use of solar thermal energy is the production of HP saturated steam for addition to the heat recovery steam generator. Also, small annual solar thermal contributions to an integrated plant can be converted to electric energy at a higher efficiency than a solar only PTC plant, and can also raise the overall thermal-to-electric conversion efficiency in the RC.

Horn et al. [42] studied an ISCCS technically and economically for implementation in Egypt. They compared two types of solar system for CC integration: PTC field and volumetric air receiver tower. Their results showed that the ISCCS with HTF-PTC is as attractive as the ISCCS with an air tower, Fig. 4 shows the integrated cycle using a solar air tower. Also, they showed that

this type of system provides an environmentally beneficial and economically attractive option for renewable power generation in Egypt. Dersch et al. [43] used GateCycle and IPSEpro software to analyse, study and compare an ISCCS with an SEGS plant and a CC plant. Their results showed that the ISCCS provides an interesting method of solar electricity generation and that the ISCCS plant has lower specific CO_2 emissions than the optimized CC plant at the same site and under the same operating conditions. Also, ISCCS provides a better solution than the SEGS plant if 24 h a day operation is required and both types have no thermal storage.

El-Sayed [44] described a new methodology for studying solar supported steam generation in CC power plants, based on modified and extended existing algorithms for unit commitment and production simulation to account for and analyse the mode of operation of these solar supported plants by considering the characteristics of the different generation sub-systems. Also, he assessed the economic impact of solar energy in the form of a cost/benefit ratio to justify the substitution potential of such clean energy. His results showed the cost/benefit ratio of the plants is 1.25–1.35 depending on their mode of operation, and the power booster mode is selected for the proposed solar supported plant due to its lower solar fraction of 8.2%, resulting in it being more economical than the fuel saving mode of the base load unit. Hosseini et al. [45] studied four configurations of solar power plants for implementation in Iran, being: SEGS, ISCCS-33, ISCCS67 and ISCCS-67AF. Their results showed that the ISCCS with 67 MWe solar fields (ISCCS-67) is the most suitable plan for the first solar power plant in Iran, Fig. 5 shows the integration scheme proposed by the authors. Baghernejad and Yaghoubi [46] assessed performance of the ISCCS with PTCs in Yazd, Iran through energy and exergy efficiencies, and the exergetic improvement potential, as well as some other thermodynamic parameters.

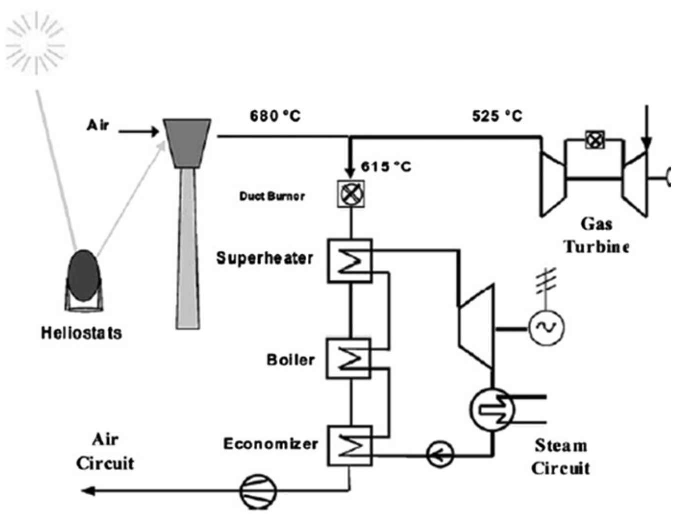


Fig. 4. Solar air tower integrated into a conventional CC at the bottoming steam cycle side [42].

Bonadies et al. [47] integrated SCR with CC and added TSS, which showed the operation hours for this new integrated cycle can be extended to 17 h using solar energy and with less running time for the GT compared with conventional ISCCS cycles. Heide et al. [48] proposed a new configuration of CC with SCR through the feed-in of solar heat directly into the GT between the compressor outlet and the combustor inlet, giving a high share of solar heat. Nezammahalleh et al. [49] assessed ISCCS-DSG technology techno-economically and compared it with two conventional cases, ISCCS-HTF and SEGS. They showed that the ISCCS-DSG is the best option for using solar energy, especially in arid countries rich in natural gas. Fig. 6 shows the conceptual design proposed by the authors. Ordorica-Garcia et al. [50] introduced three solar–fossil hybrid energy systems that are: ISCCS, solar-assisted post-combustion capture, and solar gasification with CO_2 capture. They described the features of the three solar–fossil hybrid systems, discuss its advantages and disadvantages, and provide examples of applications. Their results showed the ISCCS is the most mature of these concepts and is ready for deployment. Baghernejad and Yaghoubi [51] applied exergoeconomic principles and genetic algorithms for the optimization of ISCCS that produces 400 MW of electricity. Their results showed that the exergy and thermo-economic analysis improved significantly for optimum operation. Montes et al. [52] analysed

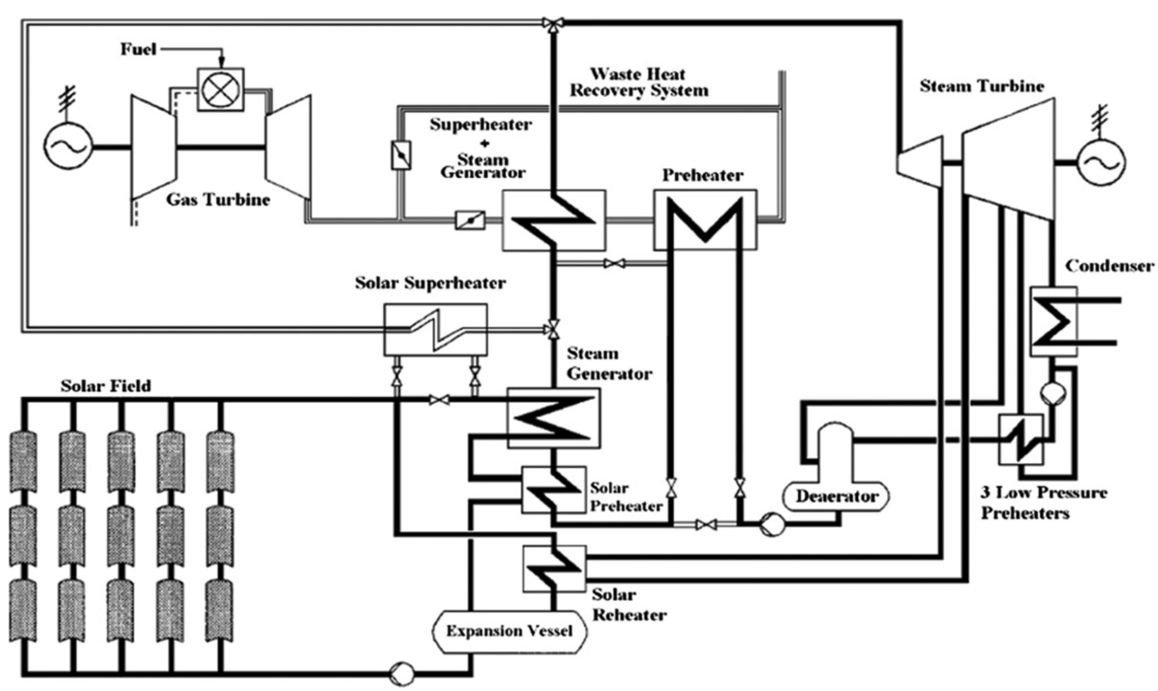


Fig. 5. Multi points integrations of PTCs to conventional CC integrated with feed water preheating, steam reheating, steam generation and steam superheating [45].

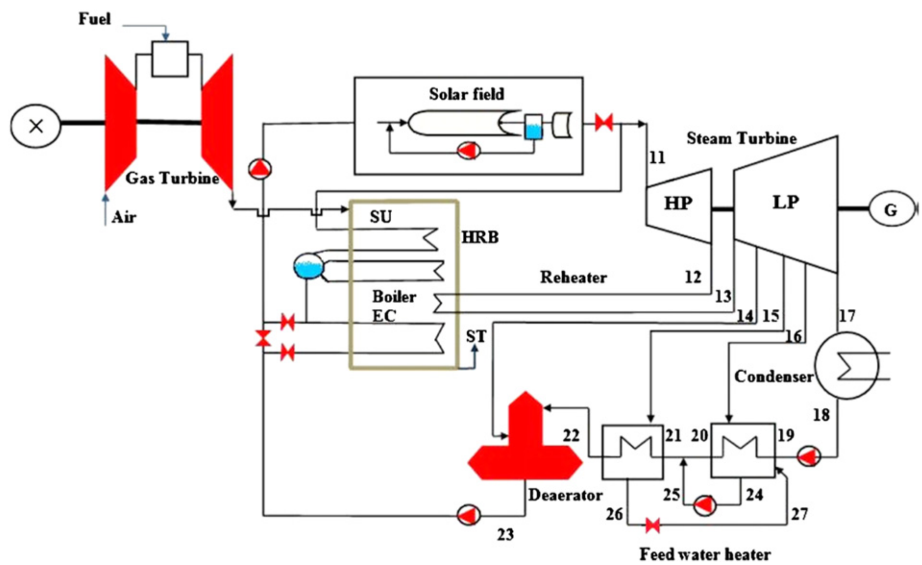


Fig. 6. Integration of PTCs to conventional CC using direct steam generation technology at steam cycle side [49].

the contribution of solar thermal power to improve the performance of gas-fired CC in very hot and dry environments in comparison to a conventional CC plant. They considered two cases for study, Almería (Spain), with a Mediterranean climate, and Las Vegas (USA), with a hot and dry climate, using the ISCCS-DSG-PTC power plant type. Their results showed that the ISCCS system operates better in Las Vegas than in Almería and hybridization between natural gas and solar power can be considered in two alternative ways: a small amount of gas complementing some deficiencies in the performance of a solar plant; or a small percentage of solar energy complementing the drop in efficiency of GTs in very hot atmospheric conditions. Their economic analysis points out that this hybrid scheme is a cheaper way to exploit concentrated solar energy, and the cost is lower in Las Vegas than in Almería.

Spelling et al. [53] developed a dynamic model of a pure-solar CC power plant to determine the thermodynamic and economic performance of the plant for a variety of operating conditions and superstructure layouts in the region of 3 MWe to 18 MWe. Also, they used this model of multi-objective thermo-economic optimization for both the power plant performance and cost using a population-based evolutionary algorithm by considering minimal investment costs and minimal levelized electricity costs. They showed that the efficiencies in the region of 18 to 24% can be achieved for levelized electricity costs in the region of 12 to 24 cent/kWhe making the system competitive with current solar thermal technology.

Derbal-Mokrane et al. [54] simulated ISCCS using the TRNSYS simulation program to determine the annual performance for Algerian data conditions, their results showed better site conditions for better power generation. Siva Reddy et al. [55] analysed an integrated natural gas-fired CC power plant with CLFR, their results showed the energetic and exergetic efficiencies of the ISCCS appear higher than in a purely solar thermal power plant and lower than a natural gas-fired CC power plant. Craig et al. [56] described a new solar–fossil hybrid design GT-PTC that combines solar contributions of 57% and higher with gas heat rates that rival those of CC natural gas plants. Their design integrates proven solar and fossil technologies, thereby offering high reliability and low financial risk while promoting solar thermal power. The results showed that a single 40-MW aero-derivative GT mated with a 100 MW PTC plant can be more efficient than two separate power plants. The estimated solar fraction for the concepts examined was 57% to 59%.

2.3. Hybrid solar–GT power plants

Pak et al. [57] proposed a hybrid-type system using fossil fuel and solar thermal energy, with solar thermal energy utilized as the working fluid of a GT in which the CO_2 generated is recovered based on the method of oxygen combustion. Their results showed that the solar thermal utilization efficiency becomes considerably higher than that of conventional solar thermal power. In another paper, Pak et al. [58] proposed a hybrid solar–GT system which recovers the CO_2 generated during combustion with oxygen. They recommended the CO_2-capturing power generation system yielding both energy savings and reduced CO_2 emissions. Buck et al. [59] tested and modified a hybrid GT with a pressurized volumetric air receiver. They examined several configurations of such hybrid systems and their results confirmed the promising potential of such technology becoming competitive with conventional plants.

Kosugi and Pak [60] evaluated the economics of two proposed solar thermal hybrid power generation systems. Each system consists of DSG solar collectors, a steam accumulator and a GT power generation system which uses steam as its working fluid. The first system emits CO_2 generated by burning fuel, while the second captures it. They showed that the captured CO_2 system is the most economical.

Fisher et al. [61] tested a hybrid solar–GT power plant integrated with an SCR, they tested fossil fuel only and hybrid modes, their main results showed that the solar–GT hybrid operation is a conceptually proven option for operation. Sinai et al. [62] studied a hybrid solar–fossil fuel operation for a solar–GT power plant. They showed that the solar Brayton cycle technology offers true capacity for utilities, a prospect of lower costs, higher efficiency, and better land usage, quick response to load fluctuations, low CO_2 emissions, easy start, and more effective equipment utilization than any other solar technology. Heller et al. [63] tested the first prototype of a solar powered GT taking many operational phases into consideration, they concluded that the volumetric pressurized receivers are able to produce air of 1000 °C to drive a gas turbine and such a system is promising for future solar generation. Schwarzbözl et al. [64] designed and assessed the performance of several prototype hybrid solar–GT plants in the power levels of 1 MW, 5 MW and 15 MW. They used advanced software tools for design optimization and performance prediction of the solar tower GT power

plants. Interestingly, their results showed that the solar–GT hybrid power technology is low cost for solar produced bulk electricity at a moderate power level. While larger units (> 10–15 MW), especially CC systems, showed very low cost for solar produced bulk electricity and small-scale units (< 5–10 MW) should be applied in distributed markets using cogeneration to start market introduction.

Gou et al. [65] presented a novel hybrid oxy-fuel GT. Solar thermal energy is used in the advanced oxy-fuel hybrid power system to produce saturated steam as the working fluid, and natural gas is internally combusted with pure oxygen. Their results demonstrated that the proposed cycle has notable advantages in thermodynamic performances and it is in configuration close to the zero emission. Garcia et al. [66] developed a model to estimate the energy performances of a hybrid solar–GT power plant according to climate, solar field, receiver, and turbine specifications, as shown in Fig. 7. Dickey [67] simulated and tested a prototype of an integrated micro GT with SCR, he proved that this prototype is able to demonstrate sustained solar power generation. Barigozzi et al. [68] simulated solar–GT with SCR using TRNSYS and THERMOFLEX software tools in order to predicate the performance of such hybrid cycles, they showed a detailed performance comparison between conventional GT power plants and solarized plants. Livshits and Kribus [69] performed thermodynamic analysis for the integration of solar concentrating collectors into conventional steam injection GT power plants, as shown in Fig. 8. They achieved improvements in performance factors as well as increasing the solar fraction up to 50% at the highest augmentation levels.

2.4. Integration schemes for conventional power plants

Many integration schemes have been suggested, developed and studied by authors. Table 1 shows the integrated parts of conventional steam power plants as well as the types of integrated Solar Thermal System (STS) for major works in this field. The most interesting thing here is the benefits of this integration from both the technical and economic viewpoints, shown by the authors through different methods and levels of integration using different types of STSs. Among the integration schemes described in the previous section, feed-water preheating is the most interesting method of using solar thermal energy with steam cycle power plants due to the positive impacts on the conventional steam cycle [21].

Table 2 shows the integration schemes used by authors to solarize conventional CC power plants as well as to specify where the solar heat/steam goes, as this type of power plant has steam bottoming and gas topping cycles and it is important to show where and how the solar thermal power is integrated. A wide range of published papers in this area focused on steam cycle integrations at multi-points and on multi-levels. This type of integration allows the integration of different types of STSs and uses solar thermal energy as a secondary source; in this way there is flexibility in operation and plant stability, as well as technical and economic benefits, while the topping gas cycle integration is limited to using an SCR at the GT side in most discussed papers due to the need for high temperature levels.

For GT power plants, integration was shown in two main ways. First, integration using high temperature levels through integrating

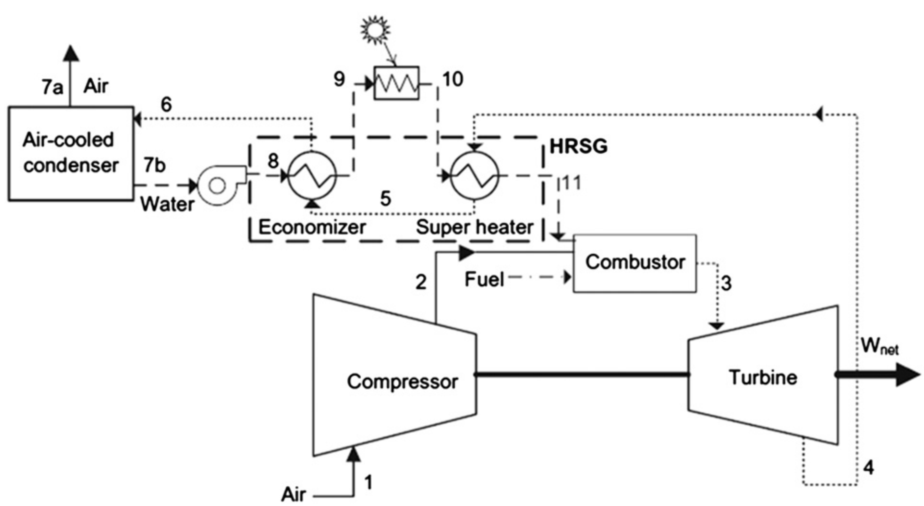


Fig.7. Proposed hybrid solar–fossil GT power plant [66].

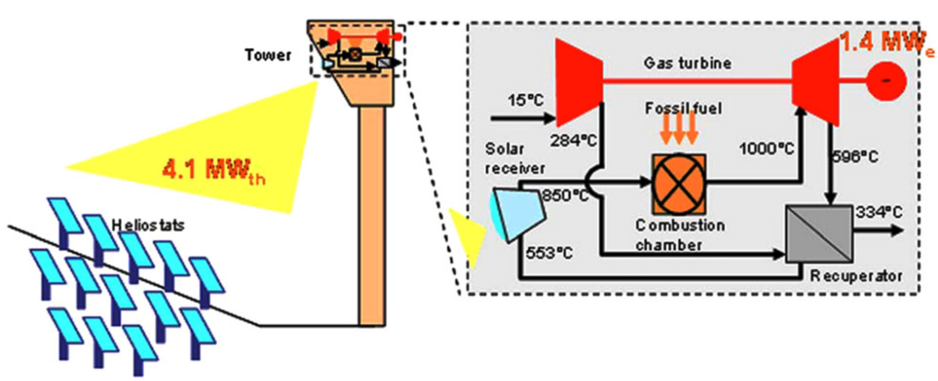


Fig. 8. Proposed solar field integration into conventional steam injection GT power plants [69].

Table 1
Integration schemes for major works of hybrid conventional steam power plants with solar thermal systems.

Author(s)	Type of integrated solar system	Integrated part of steam power plant
Zoschak and Wu [4]	SCR-DSG	FWH(HP+IP), EV, SH, EV+SH, RH, AH, AH+FHW
Griffith and Brandt [5]	SCR+TSS	Boiler
Pai [6]	PTC-HTF	All FWHs (add shell and tube heat exchanger before each one)
Ying and Hu [10]	FPC-HTF, PTC-HTF	All FWHs, LPFWH
Odeh et al. [14]	PTC-DSG	All FWHs, EV and All FWHs+EV
Gupta and Kaushik [19,20]	PTC-HTF, PTC-DSG	FWHs (replacing single separated heaters) and de-aerator
Hu et al. [21]	CLFR-HTF, FPC-HTF, ETC-HTF	FWHs (replacing single and groups heaters at multi-integration levels)
Yan et al. [22]	PTC-DSG, SD, SCR-HTF	FWHs (replacing single heater at multi-integration levels)
Suresh et al. [24]	PTC-DSG, PTC-HTF	HP FWH
Jun [25]	PTC-DSG	Boiler - Economizer (after and before)
Popov [26]	CLFC-DSG	LPFWHs, HPFWH, and HPFWH+ Economizer
Xiuyan et al. [27]	Solar field-HTF	De-aerator
Yang et al. [28]	PTC-HTF, FPC-HTF	FHWs (replacing single and groups heaters) and de-aerator
Reddy et al. [29]	CLFC	FWHs

Table 2
Integration schemes for major works by authors for CC power plants with solar thermal systems.

Author(s)	Type of integrated solar system	Integrated part	Integrated cycle
Allani [33]	PTC-HTF	HRSG	Steam cycle
Kribus et al. [39]	SCR-HTF	Between compressor and turbine	Gas cycle
Kelly et al. [41]	PTC-HTF	HRSG	Steam cycle
Horn et al. [42]	PTC-HTF, SCR	HRSG	Steam cycle
El-Sayed [44]	PTC-DSG	LP-ST	Steam cycle
Hosseini et al. [45]	PTC-HTF	FWH, EV, SH, and RH	Steam cycle
Baghernejad and Yaghoubi [46]	PTC-HTF	HRSG	Steam cycle
Bonadies et al. [47]	SCR-HTF-TSS	HRSG	Steam cycle
Heide et al. [48]	SCR-Direct solar heat	Between compressor and combustion chamber	Gas cycle
Nezammahalleh et al. [49]	PTC-DSG	FWHs+HRSG	Steam cycle
Garciaa et la. [50]	PTC- HTF	HRSG	Steam cycle
Baghernejad and Yaghoubi [51]	PTC-HTF	HRSG	Steam cycle
Montes et al. [52]	PTC-DSG	FWHs	Steam cycle
Spelling et al. [53]	SCR-HTF-TSS	Between compressor and turbine	Gas cycle
Derbal et al.[54]	PTC-HTF	HRSG	Steam cycle
Reddy et al.[55]	CLFC-HTF	FWHs+HRSG	Steam cycle

the SCR into the combustion chamber; in this way the mode of the solar–fossil hybrid can provide many advantages through flexible operation and dependability and can be used for power generation purposes. The second integration method depends on using a low temperature STS; the main purpose of this hybrid system is to use solar heat to improve the combustion process as well as to reduce emissions. Table 3 shows the integration schemes for major works in this field and the benefits of this integration. In previously published review papers [70–80], all types and technologies of STSs were described, evaluated and compared with each other from both technical and economic viewpoints, as well as with respect to their potential for deployment in different areas in the world, like India, China, Serbia, Turkey, Thailand, Germany, and Arab countries. Different types of STSs were used by the authors to repower different types of conventional power plants as shown in Fig. 9. The PTC type, for both DSG and HTF technologies, is the most common as it is more promising and economical and has been deployed worldwide [81–83]. In addition, the technical conditions for PTCs make them ideal for a wide range of applications, especially for existing plant and integration purposes. The SCR type in most cases is used for high temperature limits and thus it is used in integrating GT power plants that need higher temperatures of the working fluid, but this does not prevent their use in other applications, such as steam generation in steam and CC power plants. The other types of STS, such as CLFR, FPC, and SD, also integrate into conventional power plants but in a more limited range compared with PTCs and SCRs.

Table 3
Integration schemes for major works by authors for GT power plants with STSs.

Author(s)	Type of integrated solar system	Integrated to	Purpose of integration
Pak et al. [57]	PTC	Combustion chamber	Reduce emission
Pack et al. [58]	PTC	Combustion chamber	Reduce emission
Buck et al. [59]	PTC	Combustion chamber	Reduce emission
Kosugi and Pak [60]	PTC-DSG	Combustion chamber	Reduce emission
Fisher et al. [61]	PTC	Combustion chamber	Reduce emission
Sinai et al. [62]	SCR	Combustion chamber	Hybrid operation
Heller et al. [63]	SCR	Combustion chamber	Hybrid operation
Schwarzbözl et al. [64]	PTC	Combustion chamber	Reduce emission
Gou et al. [65]	PTC	Combustion chamber	Reduce emission
Garcia et al. [66]	SCR	Combustion chamber	Hybrid operation
Dickey [67]	SCR	Combustion chamber	Hybrid operation
Barigozzi et al. [68]	SCR	Combustion chamber	Hybrid operation
Livshits and Kribus [69]	PTC	HRSG	Reduce emission

In order to evaluate, study and develop these hybrid systems, a wide range of software tools are used by the authors; some of them used classical programming tools like MATLAB to perform their work, while many others used package software tools for that purpose. Table 4 shows the most used tools by the authors of some key works. TRANSYS software is the most often used for STS [84].

3. Integration of solar thermal with non-conventional power plants

For only geothermal power plants are there studies and published papers on their integration with solar thermal energy, this is due to the cycle configuration and requirements. The focus in previous papers deals with the solar-thermal–geothermal hybrid system (STGHS). The studies of this type of integration started in the 2000s. Kondili and Kaldellis [85] proposed an integration solution for the energy system configuration and design for the STGHS. Their results showed that the proposed analytical solution exploits local clean energy sources, and, more specifically, geothermal and solar energy, achieving promising technical and financial efficiency in the energy use of a greenhouse.

Many alternatives for the integration of a solar field with a geothermal power plant were presented by Lentz and Almanza [86–88] for possible application in the Cerro Prieto field in Mexico. The first alternative sets the solar field between the wells and the first steam separator; the second sets the solar field between the first and the second steam separators; while the third uses the leftover water from the cooling towers to produce steam in the solar field, which is sent to the first steam separator as shown in Fig. 10. All these suggested configurations are based on the DSG concept, where the geothermal brine is evaporated by flowing directly into the solar collectors. They showed that it is possible to increase the steam flow from geothermal wells using solar collectors; also, the capacity factor of the geothermic plant could be improved by increasing the amount of steam generated.

Zhang et al. [89] integrated a PTC field into a geothermal power plant to produce superheated steam. They found that the solar field makes a large contribution to increasing the power output by 10% compared to a stand-alone geothermal power plant. Ostaficzuk [90] proposed a hybrid solar–geothermal power plant as a solution for climatic constraints. Astolfi et al. [91] analysed a combined concentrating solar power system and a geothermal binary plant based on an organic RC. Their results showed that the solar–geothermal hybrid concept could represent a good opportunity for lower cost electricity production from the sun, at the same time increasing the attractiveness of many geothermal sources.

We should mention here that, in most published papers regarding STGHS, the PTC solar field is used in most cases for integration purposes while there is no use of other types of STS, and this opens the way for more studies on using other systems with different configuration schemes. Also, all authors proved the benefits of this type of hybrid system from the technical viewpoint but they need to be proved from the economic viewpoint.

4. Conclusion

A review of conventional and non-conventional hybrid solar–thermal power plants was carried out on the studies and published papers for the last three decades. It is clear that there has been the intention to search for and study such technologies in

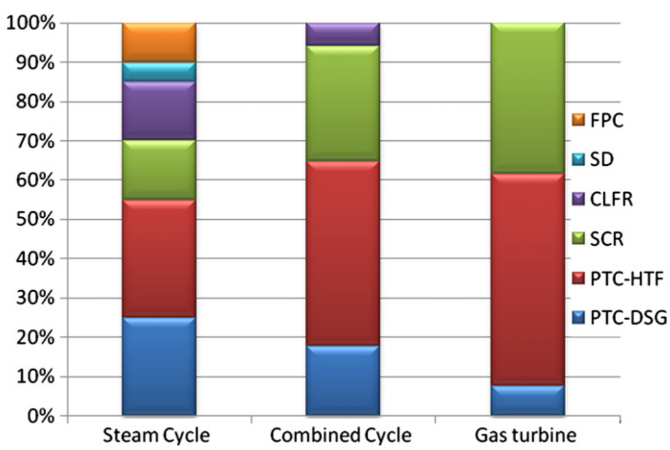


Fig.9. Percentages of using different types of STS for integration into conventional power plants.

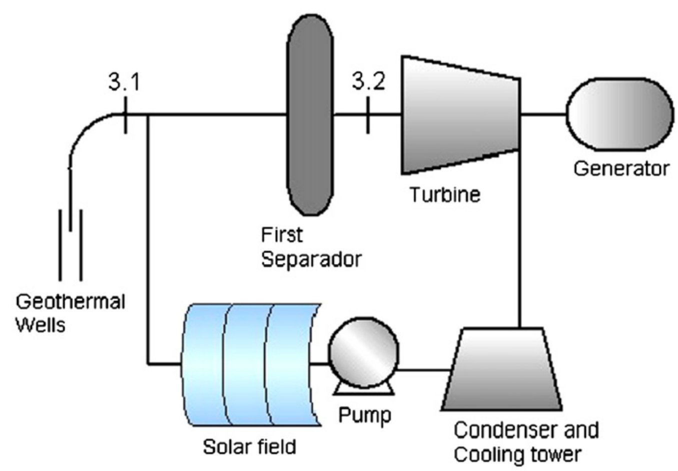


Fig.10. One alternative to the integrated solar field with a geothermal power plant [88].

Table 4
Software tools used by authors.

Authors	Software tool
Odeh et al. [7], Bockamp et al. [15], Derba-Mokranel et al. [54], Barigozzi et al. [68]	TRANSYS
Hu et al. [21][a]	THERMOSOLV
Suresh et al. [24]	Cycle tempo
Popov [26], Barigozzi et al. [68]	THERMOFLEX
Camporeale et al. [31], Kelly and Hale [41]	
Dersch et al. [43]	Gate Cycle
Dersch et al. [43]	IPSEpro
Dickey [67]	MATLAB Simulink

[a] Developed by authors.

the last decades. The main cause has been increasing fuel prices and growth awareness about climate global warning, in addition to the technical and economic advantages of hybridization. Many methods were used by the authors to analyse the hybrid cycles, some of them using compact software tools like TRANSYS, the most used tool in analysing and simulating STS, while the others used classical programming analysis methods based on the first and second laws of thermodynamics. The most useful analysing method used by the authors is based on exergy principles. Also, many methods of optimizing these hybrid systems where used by the authors for optimized synthesis, operation and design of these new systems. Compared with SCR and other types of STS, PTCs are the most interesting type of solar collecting system used by the authors for integration purposes due to their proven technology and commercialized use in many operations over the years through deployment of many such solar type plants around the world. TSS is used to a limited extent due to its high cost and is still subject to modification. In addition, compared with other types of hybrid system, ISCCS is more interesting due to its technical and economic advantages over other types and also the recent plans to deploy such power plants in many regions in the world, such as Spain, Tunisia, Egypt, and Iran.

In the end, the hybrid solar-thermal–fossil-fuel power plant concept can offer huge advantages, especially for existing power plants. Also, more studies are needed to overcome the technical and commercial problems and to apply advanced optimization methods for a more economic and reliable technology.

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